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Envelope retrofit in hot arid climates

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Abstract

This article aims to evaluate envelope retrofit as a tool to decrease reliance on air conditioning units in hot arid climates. Energyplus is used to model an apartment block in Cairo and analyze its energy performance. Retrofit through glazing improvement is evaluated in relation to cooling load and carbon emissions. Results provide guidance for envelope retrofit as a part of a plan to empower energy efficiency in Egypt and hot arid countries.

Peer-review under responsibility of the organizing committee of SBE16.

Keywords: Energy efficiency; Envelope retrofit; Energy policies; Simulation; Hot arid climates

1. Introduction

The residential sector is a major consumer in Egypt. In 2013, it consumed 42.6% of national electrical consumption. In addition, consumption increase is more than 5% annually with rising carbon dioxide emissions [1]. Statistics have shown a sharp rise in the use of mechanical cooling as a solution to climate change and heat waves in summer. In 2015, temperatures in Cairo arrived to 45°*C* due to heat waves and about 20% of energy consumption. Statistics show that between 1996 and 2010, sales of ACUs have increased from 54,000 units per year to 7,66,000 units per year [3]. The existing building stock is informal and compliance with Building Energy Efficiency Building Code is almost inexistent [11, 12]. It is necessary to investigate suitable retrofit strategies that can be adopted and applied within the Egyptian housing context.

Cairo has hot arid climate which very low precipitation and mild winters. 92.5% of Cairene Households are living in one apartment blocks. Just by walking through the streets of Cairo, it would be easy to notice the spread of linear apartment blocks [5]; linear apartment blocks is an internationally widespread typology that appeared in the late 19th century as an urban planning leitmotif of modernism. It promoted lower density housing compared to tower blocks and promoted air, sun & light. However, apartments in linear blocks in Cairo consume more energy compared to long compact towers. Electricity is one of the main energy sources in Egyptian houses; it arrives to 99% of households [8].

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The housing sector in Egypt is dominated by private owners that consider quality aspects as a secondary priority and this had its impact on the construction process and the building envelopes [9,10]. Reinforced concrete column and beam structural system with bricks for walls is the dominant method used for residential construction since the 1950s and it is almost exclusively used with the flat slab for apartment blocks. This is due to material availability, common knowledge, easy application, time efficiency and economic convenience. Glass windows with wooden shutters are mostly common for openings. Windows are single glazed, transparent and usually are formed of very thin glass layer. A recent study has proposed a plan for energy empowerment in the residential sector through Building Energy Efficiency Code enforcement and energy retrofit as an inevitable path for an effective change in consumption patterns. However, it is still necessary to investigate suitable retrofit tools and their applicability [6]. Replacement of existing window glass panes is investigated as an efficient method to decrease summer heat gain towards internal spaces and hence decrease cooling demand. The results will provide guidance for the development of a tool that aids to a successful energy requalification process.

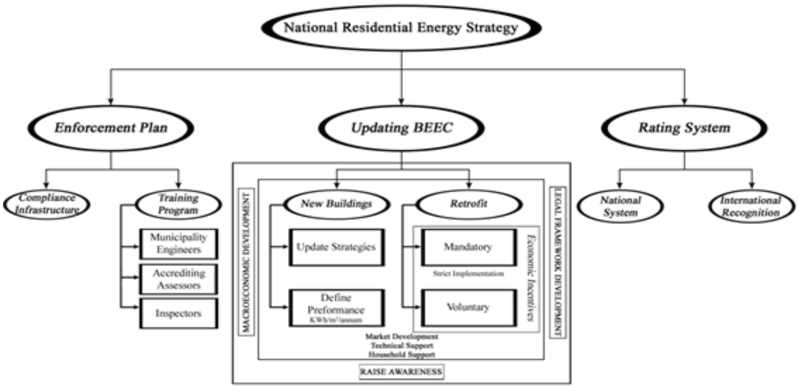

Fig. 1. National residential energy strategy proposed.

2. Aim of work and Methodology

This paper aims to investigate envelope retrofit as a tool to increase comfort levels and decrease cooling loads with consequent energy reductions in the residential sector of Cairo-Egypt as an example of hot arid climates. EnergyPlus is used to model a typical apartment block, evaluate its performance and improvement potentials through envelope retrofit strategies within the Cairene climatic context. It aims to investigate retrofit through glazing improvement as a strategy to decrease heat flows towards inner spaces during summer season and decrease annual cooling load. The study analyzes energetic and environmental aspects through energy consumption and carbon emission analysis. Results provide guidance for envelope improvement as a tool for efficient retrofits to reduce consumption rates and empower energy efficiency in Egypt and hot arid countries.

The first step was to choose a base case that is representative of the residential sector in Egypt and its energy patterns. So revision of previous survey work and studies in Egypt and Cairo was executed. The revised sources included official data by governmental institutions and research work by scholars. The case study for this work was chosen based on statistical confirmation of the presence of the building typology, the repetition of that typology in surveys that focused on or included Cairo and included energy data for audit results confrontation, and the presence of air conditioning units (ACUs) in the chosen base case. A field survey was made after to investigate the validity of the chosen model. Then, building audit and energy performance monitoring –through utility bills- was executed to understand actual performance levels. Audit data were inserted into a simulation model and its energy performance was assessed and calibrated. Retrofit strategies are defined and their impact on the simulated model is investigated through numeric results. Each strategy is evaluated in relation to the cooling load –energy consumption- and carbon emissions. The following sections provide a description of the executed steps.

Fig. 2. (a) Case study orientation in relation to the existing context; (b)Case study floor plan.

3. Building Audit

The case study is located in Cairo in MAM [2]; it corresponds to the benchmark morphology, construction technology and context [3]. The case study is a linear apartment block of six floors and two apartments per floor. The apartments are occupied by families that have two to three children with total occupancy of 4-5 pers/apt. Each apartment includes three bedrooms, a living room, a kitchen and a bathroom. The building is made of reinforced concrete skeleton with brick. External walls and interior partitions have 25*cm* and 12*cm* thickness respectively. The windows are glazed with single clear 3*mm* glass. Windows have exterior venetian wooden shutters that are almost always closed during hot periods. Airtightness is very low and infiltration can be observed throw window frames. Suspended fluorescent light is used in almost all spaces except the living rooms which have incandescent suspended units. Lighting operation hours are dependent on space occupancy hours which were investigated through field surveys. Water heating is a minor consumer in Egyptian houses. Stand-alone water heaters with liquid petroleum gas are commonly used to provide hot water in kitchens and bathrooms.

Table 1. Building Description.

Location	29°87 latitude / 31°33 Longitude
Shape	Rectangular
ASHREA climate type	4B
Orientation	North-South
Environment	Adjacent blocks of similar thermal conditions
Construction	Reinforced concrete skeleton and red brick walls
Number of floors	6
Floor Area (*m2*)	234
Floor Area (*m2*)	234
Net conditioned Floor Area (*m2*)	107 (45% of total floor area)
Floor Height (*m*)	3
Façade surface area (*m2*)	204
Glazing area (*m2*)	51
Glazing ratio (%)	25%

Natural ventilation is necessary for providing minimum fresh and as cool interior spaces. However, starting early May and until the end of September, ventilation is kept to the minimum to avoid heat flows that come from outside, and reliance on ACUs becomes high to maintain inner spaces within comfort temperatures. Cooling units are used in bedrooms and living rooms. Split Wall Mounted Air Conditioners are common and portable fans are used for unconditioned spaces.

4. Energy performance monitoring

It was complicated to obtain utility bills from all apartments because some families didn't have all monthly bills of 2014 and others considered it as an invasion of personal privacy. However, it was necessary to collect bills to audit energy performance, compare it with past consumptions [2] and create a credible representative simulation model. It was necessary to audit different floors' consumption as they have different subjection to solar radiation and climatic conditions. Intermediate floors appeared to have relatively close utility bills with slight increase in consumption rates for higher floors. It was clear that 6th floor apartments had higher bills as they are directly subjected to solar radiation which increased operation hours of the ACUs during summer, while ground floor apartments had significantly lower bills. Gradual rise in consumption can be observed starting March until the peak in August where electricity bills increase up to 3 times higher due to extra cooling load. A field survey showed that 41% of the users turned on ACUs when inside temperature exceeded 26-27°*C* in summer. Also, 96% avoided turning ACUs when spaces weren't occupied to avoid higher bills. These patterns were inserted to the simulation software to create a human like behavior and guarantee accurate results.

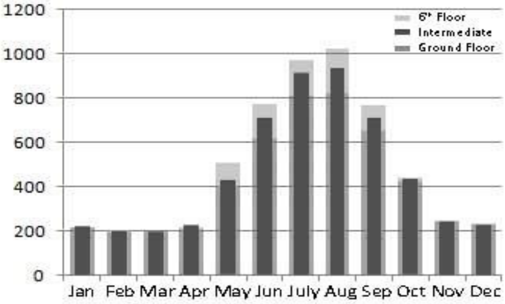

Fig. 3. Average monthly consumption of apartments in kWh according to utility bills.

5. Model Calibration

The choice of a simulation tool is an influential factor in results accuracy and correspondence to a given base case. Designbuilder (DB) was chosen for simulation for its accuracy of thermal simulation, ease of alternatives' analysis and the user friendly interface it provides. It is a trusted tool based on Energyplus that is funded by the U.S. Department of Energy Building Technologies Office and has been approved for England and Scotland energy performance certificates necessary to build, sell or rent a property.

DB provides a systematic framework to calibrate the model; it requires detailed definition of weather data, zone division, construction materials, openings, space activity & occupancy rates, light & equipment, domestic hot water, natural ventilation rates and HVAC systems. The case study was modelled and simulated to test its thermal behaviour. It is oriented north-south and considers adiabatic lateral adjacencies ''i.e. the block is attached to other blocks that have similar thermal conditions''. Spaces are physically defined and are considered as thermal zones that react with adjacent spaces and outside environment through heat transfer, thermal conduction and thermal convection principles. The model has external walls of 25*cm* brick with portland cement mortar and paint on both sides. Interior partitions are made of 12*cm* brick with portland cement mortar and paint on both sides. Ground floor slab, intermediate slabs and roof slabs have different sections. Bituminous waterproofing is used to protect the ground and floor slab from humidity and rain. The roof has 5*cm* extra sloped concrete layer to direct the rain water towards water ducts for drainage. It is also thermally insulated with a 6cm layer of Expanded Polystryene sheet to decrease the impact of perpendicular incident solar radiation. Windows have wooden and metal frames with 3*mm* clear glazing of low thermal insulation properties. Medium venetian blinds are positioned on the outside of each window and model infiltration is 0.7 ac/h. Table 2 shows the building envelope solid elements and its characteristics.

Apartment density is 4.19 person/apartment according to national census and site visit has confirmed that most families are composed of four to five members per apartment. Suspended light with 4 *W/m2* -100*lux* surface power densities is used to acquire average illuminance levels required by BEEC during occupancy hours. Stand-alone water heaters are used for hot water in kitchens and bathrooms. Fresh air requirements are 3L/sec/person for living room and bedroom, and 14L/sec/person for kitchen and bathroom. Ventilation occurs when the temperature of occupied spaces exceeds 23°*C* and outside air temperature is lower than inside air temperature. This helps increase cooling, air movement and heat loss. When natural ventilation fails to maintain a 26°*C* or lower temperatures, mechanical cooling operates to maintain space temperature within that setpoint during occupancy. Split wall mounted units with coefficient of performance and capacity 3.26 and 18000btu respectively are used to cool two bedrooms and the living room in each apartment. This sums up to 36 ACUs for the whole apartment block.

Table 2 Envelope Description.

	U_{value} *W/(m²-K)*	R_{value} *(m²-K)/W*	Internal heat capacity *KJ/(m²-k)*
25 cm thick red brick with 2.5 cm thickness of Portland cement mortar and paint on both sides	1.319	0.758	150.0324
12 cm thick red brick with 2.5 cm thickness of Portland cement mortar and paint on both sides	1.819	0.550	150.0324
Ground Floor Slab	1.436	0.696	180.733
With Bitumen Insulation			
Typical Floor Slab	1.302	0.768	153.2432
Roof Slab with Bitumen and Expanded Polystyrene Insulation	0.337	2.97	190.4

6. Simulated Model Validation

The building was simulated for a complete year (8760 hours), calibrated computational consumption rates were compared to documented consumption rates from utility bills in *kWh*. The simulated model building site energy is 67320 *KWh* compared to 64049 *KWh* surveyed energy consumption with 4.8% inaccuracy. However, this is an acceptable error margin considering the complexity of software equations and their underlying numerical mechanisms that make it a hard task to perfectly model annual human behavior. Hence, results of the building energy model are considered corresponding to surveyed data with high accuracy and its computational predictive capability is considered credible.

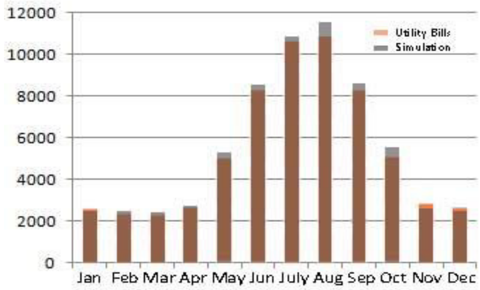

Fig. 4. Building monthly model data compared to surveyed data.

7. Simulated Energy Performance

The building total site energy is 67320 *kWh* causing 31115 *KgCO2e* carbon dioxide emissions annually. Cooling, interior light, domestic appliances and water heating consume 35789 *kWh*, 8777 *kWh*, 3052 *kWh* and 293 *kWh* respectively. Cooling accounts for 53% of total energy consumption and causes 16541 *KgCO2e* carbon emissions annually. Average energy per total building area is 49.59 *kWh/m2* and energy per conditioned building area is 109 *kWh/m2* accounting for more than the double.

Table 3. Energy data.

Total annual consumption (per building)	67320 *KWh*
Total annual consumption (per apt.)	5610 *KWh*
Total annual Co2 emission (per apt.)	2593 *KgCO2e*
Energy Per Total Building Area	49.59 *KWh/m2*
Energy Per Conditioned Building Area	109 *kWh/m2*

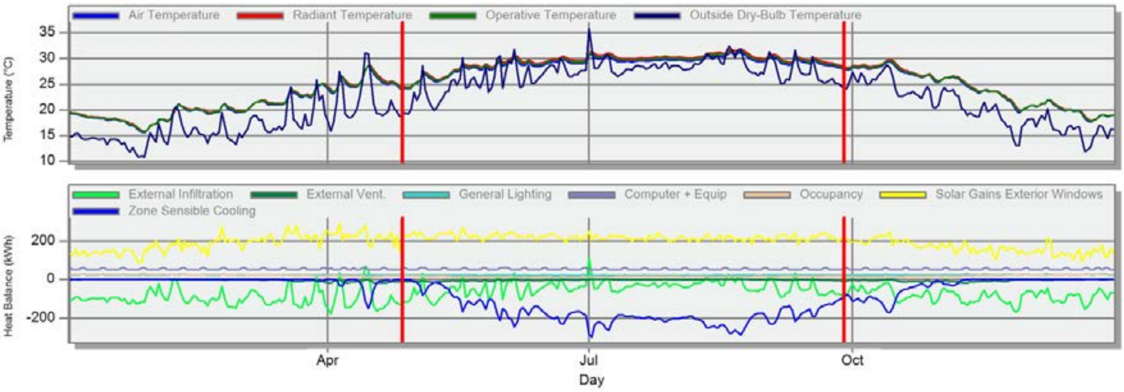

Fig. 5. Annual profile of the whole building.

Figure 5 shows outside dry-bulb in relation to air radiant and operative temperatures of the building during a complete solar year. It also shows the heat balance in *kWh*. Exterior windows are the main cause of solar gains. This becomes a problem in summer when solar heat gains from exterior windows result in more than 200 *kW* increasing the cooling load on ACUs. Cooling starts to operate slightly in March and April, then increases to arrive to its peak in June when total cooling reaches more than 300 *kW* total and it doesn't start to decrease before September. Space infiltration causes more heat loss during winter compared to summer due to higher exterior temperatures in summer. Domestic appliances and computers are also a main cause of heat gains all year long. However, it comes secondary in respect to gains from windows.

Figure 6 shows the daily profile on the 15th of July, outside maximum dry-bulb temperature occurs at 15:00 and lags the maximum solar elevation by three hours. Internal temperature shown is an average for the whole building and space temperatures are best viewed at zone level. However, the graph gives a global view of the whole building and its daily profile. For example, operative temperatures sharply increase after 7:00am when the cooling units stop working, hence raising the temperature of the whole building. Artificial cooling works in the evening in the living room then in the bedrooms during the night. It is used less during the day because there is no –or very low-occupancy. The cooling units work when bedrooms and living rooms have required minimum occupancy. This can be seen when bedrooms are occupied for sleep and ACUs are turned on causing a stable load of about 10 *kW* from 12:00 till 7:00am. Relative humidity is directly relevant to cooling operation hours; it drops gradually from 38% to 32% when the cooling units are turned off. Infiltration provides a stable value of 0.7 ac/h and ventilation is very low -almost inexistent- because outside air temperature is higher than space temperature most hours spaces are occupied and when outside air temperature drops, it's still higher than the required comfort setpoint 26*°C*.

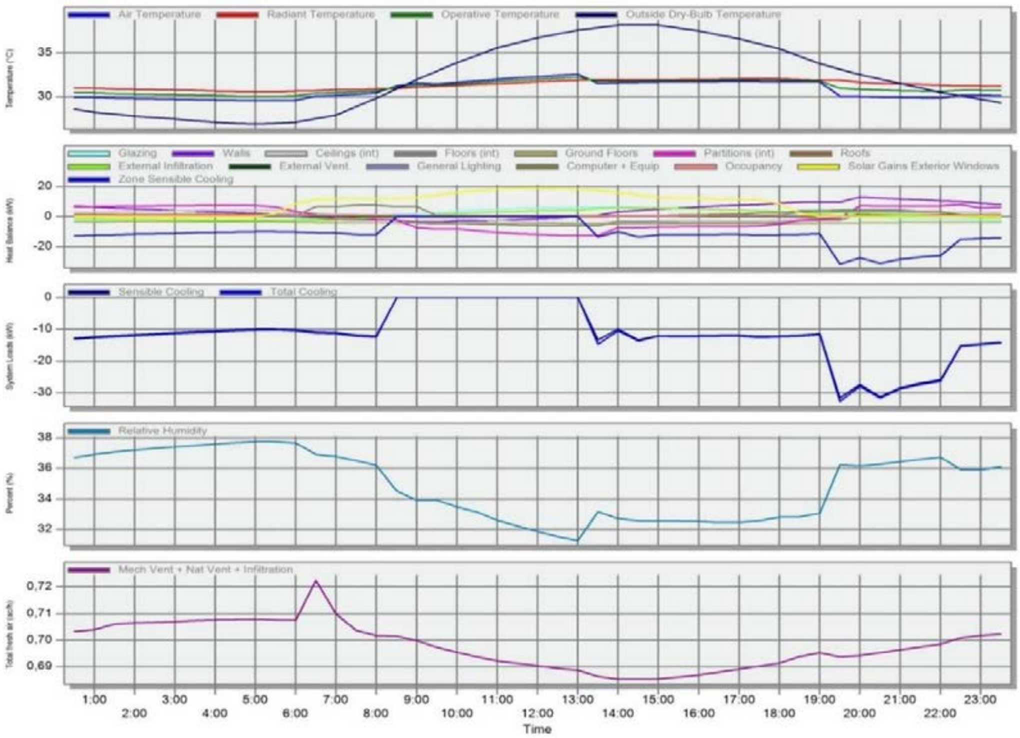

Fig. 6. Daily profile of the whole building on the 15th of July.

8. Retrofit

An efficient envelope retrofit for cooling load dominant climates requires reduction of solar gains through the envelope, increasing resistance and infiltration control. Retrofit choice requires great attention to energy, environmental, social and economic aspects to obtain applicable solutions. This study aims evaluate energy and environmental aspects through energy consumption and carbon dioxide emission reductions.

Site direct solar radiation during summer is 0.8 *kW/m²* starting 9:00am till 7:00pm; Maximum solar radiation occurs at midday 0.86 *kW/m²*. Diffuse horizontal solar radiation maintains a stable value of 0.11 *kW/m²*. In a summer day, solar gains from exterior windows and glazing add up to 20 *kWh* load in inner spaces. Replacement of existing window glass panes is an efficient method to decrease summer heat gain and hence decrease cooling demand in conditioned spaces and increase thermal comfort hours in unconditioned spaces.

The case study's current glazing is single 3mm clear glass of thermal transmittance of 5.894 $W/(m^2\text{-}K)$ and Solar Heat Gain Coefficient of 0.861. The impact of glazing replacement has been evaluated and its relation to the cooling load has been documented. The investigated glazing strategies include thicker glass, grey glass, double, triple and quadruple LoE glazing. LoE glazing has Low-emissivity metallic coating on one or more panes. So triple LoE film (33) bronze 6*mm*/13*mm* air window is composed of the following layers: 6*mm* bronze as an outside layer, 13*mm* air layer, coated poly-33 layer (i.e. coated polyester film with nominal visible transmittance of 33%), 13*mm* air layer, and a clear 6*mm* glazing from the inside. Quadruple LoE film (88) 3*mm*/8*mm* krypton is composed of an outside 3*mm* clear glazing, 8*mm* krypton, coated poly-88, 3*mm* krypton, coated poly-88, krypton 8*mm* and a clear glass 3*mm* interior layer. The proposed strategies are evaluated based on the following characteristics:

- U_{value}: Nominal Center-of-glass U_{value} ($W/(m^2\text{-}K)$) calculated for winter conditions (i.e. -18C outside air temperature, 21*°C* inside air temperature, 5.5 m/s wind speed and zero solar radiation)

- SHGC: Solar heat gain coefficient of the construction calculated for summer conditions (i.e. 32°*C* outside air temperature, 24°*C* inside air temperature, 2.8 m/*s* wind speed and 783 *W/m2* incident beam solar radiation normal to glazing
- SC: Shading coefficient of the construction
- TSOL: Solar transmittance at normal incidence of the construction
- TVIS: Visible transmittance at normal incidence of the construction

Table 4. Characteristics of proposed glazing.

Glazing Type	U_{value} W/(m^2-K)	SHGC	SC	TSOL	TVIS
Single Clear 3mm (Base Case)	5.894	0.861	0.99	0.837	0.898
Single Clear 6mm	5.778	0.819	0.94	0.775	0.881
Single Grey 3mm	5.894	0.716	0.82	0.626	0.611
Single Grey 6mm	5.778	0.602	0.67	0.455	0.431
Double Grey 6mm/13mm Air	2.716	0.611	0.70	0.526	0.551
Double Grey 6mm/13mm Arg	2.511	0.499	0.55	0.354	0.381
Triple LoE Film (66) Bronze 6mm/13mm Air	1.214	0.254	0.29	0.161	0.322
Triple LoE Film (33) Bronze 6mm/13mm Air	1.190	0.154	0.17	0.073	0.169
Quadruple LoE Film (88) 3mm/8mm Krypton	0.781	0.466	0.53	0.338	0.624

9. Results

Just by increasing the thickness of the existing window panes from 3*mm* to 6*mm*, it is possible to decrease annual cooling load and carbon emissions save by 388 *kWh* and 179 *KgCO2e* respectively. 3*mm* and 6*mm* single grey glazing save 1237 *kWh* and 2432 *kWh* with consequent 572 *KgCO2e* and 1124 *KgCO2e* respectively.

Double grey glazing with air and double grey glazing with Argon save 5329 *kWh* and 5443 *kWh* energy and 2463 *KgCO2e* and 2516 *KgCO2e* carbon reduction respectively. Triple LoE with 66% film and Triple LoE with 33% film save 7495 *kWh* and 11157*kWh* with a significant reduction of carbon emissions of 3464 *KgCO2e* and 5157 *KgCO2e* respectively. The quadruple glazing saves 6650 *kWh* and reduces carbon emissions by 3074 *KgCO2e*.

Quadruple Krypton glazing is less effective in comparison to proposed triple glazing windows; it has lower thermal transmittance value; however SHGC, SC, TSOL and TVIS are significantly higher. The most effective strategy is triple LoE Film (33) Bronze that reduces the cooling load by and carbon emissions resulting from it by 31.17%.

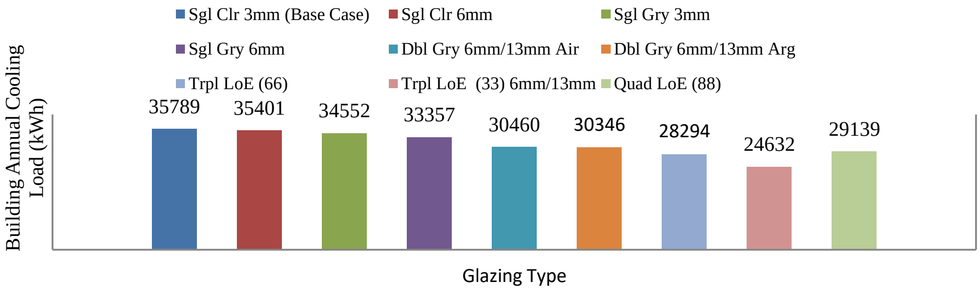

Fig. 7. Building cooling load in relation to glazing retrofits

Table 5. Retrofit impact on cooling load and carbon emissions

Glazing Type	Annual Cooling Load (kWh)	Annual Cooling load reduction (kWh)	Cooling load reduction %	Carbon emissions reduction (KgCO2e)

Single Clear 3mm (Base Case)	35789	-	-	-
Single Clear 6mm	35401	388	1.08	179
Single Grey 3mm	34552	1237	3.45	572
Single Grey 6mm	33357	2432	6.79	1124
Double Grey 6mm/13mm Air	30460	5329	14.89	2463
Double Grey 6mm/13mm Arg	30346	5443	15.21	2516
Triple LoE Film (66) Bronze 6mm/13mm Air	28294	7495	20.94	3464
Triple LoE Film (33) Bronze 6mm/13mm Air	24632	11157	31.17	5157
Quadruple LoE Film (88) 3mm/8mm Krypton	29139	6650	18.58	3074

10. Discussion

In comparison to the building state of art, where glazing transmits most heat from the outside, envelope retrofit through glazing upgrade decreased cooling load and total energy consumption. Just the replacement of a thicker and darker glazing –single grey 6mm- can achieve 2432 *kWh* less load. With the most effective strategy - triple LoE Film (33) - annual cooling can be reduced by up to 11157 *kWh* resulting in 31.17% less load on the cooling units and 16.5% reduction in total energy consumption. This corresponds to 5157 *KgCO2e* lower carbon footprint (i.e. 16.5% reduction in total building carbon emissions). Moreover, window replacement created a thermal lag of heat flow during high peak demand days, this shifts peak energy demands to off-peak hours, thus decreasing extreme peak hours - avoiding extra pressure on the electricity grid which leads to power cuts- and reducing sharp temperature rise in unconditioned spaces. Proposed strategies have higher thermal resistance; this should also decrease the loss of necessary heat in winter and increase comfort hours in colder seasons.

11. Conclusion

This study has evaluated envelope retrofit for hot arid climates. Glazing replacement only can lead up to 16.5% savings of total energy with an increase in comfort hours in conditioned and unconditioned spaces. The proposed strategies indicate a base for solution set creation that decreases energy consumption and opens the door to the potential of passive retrofits as a path towards the zero energy objectives in Egypt and hot arid countries.

12. Limitations and Future work

This work has evaluated envelope retrofit savings of a building that includes 3 ACUs per apartment. However, cooling consumption is tightly linked to the number of ACUs, conditioned space area and users' behavior. Therefore, energy consumption and reduction rates might vary with the variation of these factors. Simulation results have shown that cooling load varies from one floor to another as they are subject to different solar projection; however this study considered the whole building scale for a more complete overview. The proposed retrofit materials are locally available with competitive prices. Future work can investigate cost efficiency through a cost vs. payback time analysis.

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